

Original Articles

The land use suitability concept: Introduction and an application of the concept to inform sustainable productivity within environmental constraints



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ABSTRACT

The Land Use Suitability (LUS) concept informs decision-making by providing stakeholders with integrated information about the economic, environmental, social and cultural consequences of land use choices. This paper addresses an application of the LUS concept: evaluating the suitability of land for sustained productivity subject to environmental constraints, as defined by water quality objectives. We refer to this application of the LUS concept as 'Productivity within Environmental Constraints' (PEC). A PEC assessment uses three indicators to evaluate land-water systems: 1) productive potential, describing the inherent productive and economic potential of land parcels; 2) relative contribution, describing the potential for a land parcel to contribute contaminants (relative to other land parcels) to downstream receiving environments; and 3) pressure, describing the contaminant load delivered to a receiving environment compared to the load that ensures that environmental objectives are met. The three indicators can be expressed categorically, mapped at catchment to national scales, and used to support strategic land assessments and plan land development and investment.

1. Introduction

Intensification of primary production to meet growing demand for food and economic well-being has the potential to degrade land, water, biodiversity and climate from farm to global scales (Foley et al., 2011; Meyfroidt, 2017). It is also increasingly recognised that land use decisions have economic, environmental, social and cultural impacts beyond the farm (Goldstein et al., 2012; Liebig et al., 2017; Renting et al., 2009). In order to address the pressures on ecosystems and society, stakeholders need information that assists in understanding the implications of land uses for the full range of desired outcomes.

There are many examples of assessments of land suitability or land evaluation assessments that have built on the USDA (Klingebiel and Montgomery, 1961) and Food and Agriculture Organization (Food and Agriculture Organization, 1976) classification frameworks (Van Diepen et al., 1991). The principles behind these frameworks include assessing

the capability of the physical environment, such as climate, relief, soils, hydrology and vegetation, to support a given land use. Subsequent land evaluation systems described the biophysical constraints that limit sustained productivity and quantified production in that context (Lynn et al., 2009; Mueller et al., 2010). Production constraints include soil properties (e.g., depth, water holding capacity, erodibility), climatic conditions (e.g., rainfall, growing degree days) and risks posed by climate change. We use the term land suitability to generically refer to frameworks used to assess the capacity of land to support primary production.

As pressure to increase food production, economic prosperity and environmental sustainability grows, land suitability assessments will need to move beyond a narrow focus on agricultural productivity, and involve a broader range of factors (Foley et al., 2005). Attention has recently turned to the ways in which concepts such as ecosystem services, including contaminant assimilation, transformation and removal,

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can encourage a broader view of land suitability when considering sustained primary productivity (Doody et al., 2016; Liebig et al., 2017; Renting et al., 2009). While there are examples of systems that assess the potential of land parcels to contribute contaminants to receiving environments (McDowell et al., 2015), these have not been combined with assessments of productive potential, nor have they considered impacts on receiving environments. If sustainable productivity and environmental objectives are to be achieved, a suitability assessment system needs to provide information on all of these aspects.

We define the Land Use Suitability concept (LUS) as a framework for assessing the suitability of land for primary production that acknowledges and accounts for the connections between land use and economic, environmental, social and cultural impacts. LUS is distinct from land suitability assessment frameworks that focus only on the farm scale, and it recognises that land use impacts accumulate in space and can occur far away from individual farms. LUS seeks to promote sustainable land use by providing stakeholders with information that highlights the interconnected and cumulative nature of land use impacts. The broad scope of the LUS concept means that its practical applications need to be specific to particular contexts, scales and problems. Consequently, the selection of relevant indicators of suitability, and the way they are assessed and combined is likely to vary with each application of the LUS concept. In this paper, we discuss an application of the LUS concept to the issue of land use and its impacts on water quality in New Zealand.

In our application of the LUS concept, we use three indicators to collectively describe the suitability of land for primary production that takes into account water quality objectives in downstream receiving environments (e.g., streams, rivers, estuaries, groundwater). We refer to this application of the LUS concept as sustained Productivity within Environmental Constraints (PEC). One PEC indicator assesses productivity of land parcels, and the other two assess the impacts in downstream receiving environments. The impact indicators are based on the premise that, all other considerations aside, productive land located in catchments with lower environmental constraints is more suitable land for intensive production. Similarly, within a catchment, land that has a lower potential to cause environmental impacts is more suitable for intensive production than land with higher potential to cause environmental impacts.

The remainder of this paper focuses on the PEC assessment system. The first section sets out the conceptual basis for a PEC assessment and its three indicators. The second section describes the analytical steps involved in carrying out a PEC assessment. The third section identifies sources of data and existing models that can be used in PEC assessments. The fourth section discusses the potential range of applications, limitations and future developments for PEC assessments.

2. The conceptual basis of a PEC assessment

Our conceptualisation of a PEC assessment is based on three indicators that describe 1) the capacity of a land parcel for primary productivity; 2) the potential of a land parcel to contribute contaminants; and 3) the response of receiving environments to contaminants. In the following text, we give operational definitions for important terms, which are underlined when they first appear. We begin by defining each of the three indicators in order. First, the capacity for primary productivity is described by the productive potential indicator, which is based on the inherent potential of a land parcel for sustainable primary productivity. Second, the likelihood of land to contribute contaminants is described by an indicator that quantifies the relative contribution of each land parcel to the delivered load at any point in the catchment. Third, the response to contaminant loading in receiving environments is described by the pressure indicator. The pressure indicator recognises that receiving environments are subject to environmental objectives that define their assimilative capacity. The pressure indicator discriminates between land parcels in terms of the extent to which their productive potential may be constrained by the

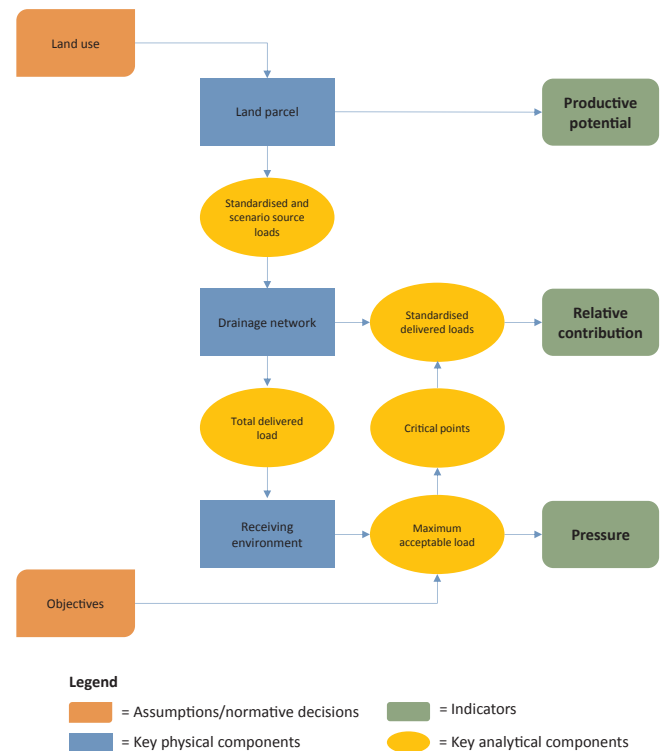


Fig. 1. Schematic diagram indicating the key physical components that comprise a land-water system and the analysis steps involved in deriving three indicators used in assessing sustainable productivity within environmental constraints within the land use suitability concept.

assimilative capacity of receiving environments.

In a PEC assessment, a category is assigned to each of the three indicators for each land parcel in a land-water system (e.g., high productive potential, low relative contribution, high pressure). Evaluating the indicators for each land parcel requires an analysis of the land-water system (Fig. 1) and involves consideration of more than one spatial scale. The three indicators describe differences between land parcels in relative, not absolute, terms. Although the indicators are derived in a catchment-specific context, they are characterised in such a way as to enable comparison of the suitability of land parcels both within and across catchments.

The current conceptualisation of PEC only considers the assimilative capacity of receiving environments for four contaminants (nitrogen, phosphorus, sediment and the faecal indicator bacterium *Escherichia coli* [*E. coli*]), and the independent effects of each contaminant. We recognise that water quality effects will arise from interactions between contaminants and other off-site impacts of land use such as reduced river and groundwater flows and levels caused by the abstraction of water for irrigation. In addition, the current conceptualisation only considers aquatic receiving environments that are connected to a drainage network. In the future, a PEC assessment could be expanded to other receiving environments (e.g., soils, atmosphere), other contaminants (e.g., cadmium, pesticides) and non-contaminant stressors (e.g., water abstraction, soil compaction), and multiple-stressor effects.

Our current conceptualisation of PEC does not consider infrastructure, cultural or societal factors that may influence the suitability of a land parcel for a specific land use (e.g., distances to processing plants, ports and labour markets). Consideration of these factors is consistent with the broader LUS concept, but their assessment would require another specific application. An exception could be the contribution of contaminants from urban sewage works, which as a monitored point source could be accounted for in a PEC calculation. In addition, a PEC assessment does not consider how shares of the capacity

for resource use of the land-water system can or should be distributed among land parcels. The sharing and distribution of capacity for resource use is an allocation decision, which involves consideration of more than just biophysical aspects of the land-water system. However, PEC assessments provide information that is relevant to allocation decisions.

3. Carrying out a PEC assessment

Carrying out a PEC assessment involves analysis of a land-water system in sufficient detail to evaluate each of the three indicators for each land parcel (Fig. 1). The representation of the land-water system, and the analyses involved, are based on further conceptual details that are shown schematically in Fig. 1 and are described in detail in the following sections.

Although the three PEC indicators are conceptually independent, they are linked by catchment processes. Therefore, some aspects of the analyses required to derive these indicators are connected and occur in the sequence shown in Fig. 1. The text below introduces the conceptual details and analyses in the same sequence.

3.1. Spatial framework

The conceptual framework for a PEC assessment begins with a spatial representation of three physical components of land-water systems: land parcels on which production occurs, receiving environments down-gradient of land parcels, and drainage networks that connect land parcels to receiving environments (Fig. 1). Together, the representation of these three physical components allows the catchments of all receiving environments and the land parcels to which each receiving environment is connected, to be identified.

The minimum geographic domain for a comprehensive PEC assessment is a catchment that drains to the sea as this incorporates a 'whole' land-water system including all relevant land parcels and receiving environments (including estuaries). Ideally, a PEC assessment would be implemented across the whole of New Zealand, thereby extending its potential uses from catchment scale to regional and national scales. While implementing a PEC assessment nationally requires national-scale representations of land parcels, drainage networks and receiving environments, higher resolution representations can also be employed for more detailed PEC assessments over smaller geographic areas.

Land parcels are the fundamental spatial entities to which indicators describing productive potential, relative contribution and pressure are assigned. The definition of a land parcel therefore determines the spatial resolution of the system. Land parcels can be operationally defined by a grid of the geographic domain, legal (cadastral) boundaries, hydrological units such as hillslope areas draining to segments of the river network, or other discrete spatial units.

The drainage network defines the flow paths connecting land parcels to their downstream receiving environments. Conceptually, all points on the drainage network are receiving environments. However, management objectives are generally designated at key locations or 'nodes'. These nodes are therefore the predefined points in the network at which the relative contribution and pressure indicators are assessed. Lake, wetland and estuarine receiving environments can be identified as nodes if they can be associated with environmental objectives. Receiving environments can be identified at different levels of spatial resolution, while environmental objectives tend to be designated for specific locations in a catchment. Therefore, some pragmatic choices concerning the spatial detail are required. For example, riverine receiving environments can be designated at significant points in the network such as at major tributary confluences associated with a change in stream order.

3.2. Productive potential

The purpose of the productive potential indicator is to discriminate between land parcels in terms of their potential for primary productivity (e.g., Mg crop dry matter ha⁻¹). Two systems in current use in New Zealand for classifying land potential for primary production based on edaphic and climatic factors are the Topoclimate system and the land use capability (LUC) system. Topoclimate classes have been used to discriminate variation in productive potential for a variety of crops (Griffiths et al., 2003; Otago Regional Council, 2017; Purdie et al., 1999; Round-Turner, 2013). The LUC system provides an indicator of the productive versatility of land parcels for a range of land uses and identifies key constraints such as erosion (Lynn et al., 2009). This system also includes indices of stock carrying capacity and forestry production.

3.3. Standardised and scenario source loads

The rate of contaminant loss from a land parcel is referred to as a source load. Source loads are expressed as mass-loss rates (kg yr⁻¹) or as rates per unit contributing area (i.e., yields; kg ha⁻¹ yr⁻¹). Expressing source loads in this way makes them amenable to analyses that represent contaminant transport and transformation (see *Delivered loads* below). Source loads are conceptualised as a function of the susceptibility of a land parcel to lose contaminants, and its land use (Kerr and Todd, 2009). In that sense they are conceptually similar to the ecoregion approach used to inform policy in the US (Omernik and Griffith, 2014). The land use of a land parcel is described by the main production system in operation (e.g., dairy, sheep and beef, viticulture, horticulture, arable). A PEC assessment requires two types of source loads to be analysed: standardised source loads and scenario source loads.

The standardised source load is used to evaluate the relative contribution indicator of a PEC assessment and describes the susceptibility of a land parcel to contaminant loss (see *Relative Contribution* below). The standardised source load is independent of land use, and assumes that the relative differences in contaminant losses between land parcels are maintained across different land uses (e.g., any land use occurring on two different land parcels would result in the same relative difference in standardised source loads). The validity of this assumption remains to be tested and will influence the choice of approaches used to evaluate standardised source loads. A range of approaches to evaluating standardised source loads can be used including:

1. derivation from fundamental soil processes that control contaminant loss,
2. use of a standardised land use across land parcels, and
3. integration across a range of losses from different land uses.

In contrast to a standardised source load, scenario source load describes the contaminant loss from a land parcel under a given land use scenario, and is used to evaluate the pressure indicator of a PEC assessment (see *Pressure* below). Conceptually, any realistic configuration of land use can be used to evaluate scenario source loads and would result in a PEC assessment that is relevant to that land use configuration. However, two specific land use configurations are particularly relevant: current land use and maximum-intensity land use. Current land use will produce an assessment of pressure that reflects current conditions. A maximum intensity land use configuration would allow an assessment of pressure corresponding to the 'full utilisation' of productive potential of the catchment.

3.4. Delivered loads

Contaminant source loads from land parcels are transported to downstream receiving environments via the surface and groundwater

drainage network. Contaminant delivery to a receiving environment is a function of the upstream source loads, and transport, transformation and sequestration processes that affect contaminant loads in the drainage network (e.g., biological assimilation, remineralisation, adsorption, desorption, sediment deposition and erosion). Some transformation processes permanently remove contaminants from the network, thereby reducing both concentrations and load (e.g., denitrification, microbial die-off); reduction in source load via removal processes is termed attenuation. Other transformation processes sequester contaminants then release them in the same form (e.g., transient storage) or in different forms (e.g., nitrate assimilation by algae and bacteria, followed by dissolved organic nitrogen release).

A PEC assessment involves deriving the delivered component of both standardised and scenario source loads. In both cases, the delivered component represents the difference between the source load and attenuation that occurs on the drainage path. The standardised delivered load is the delivered component of the standardised load for each land parcel, and is expressed as a yield ($\text{kg ha}^{-1} \text{yr}^{-1}$). The standardised delivered load is used to calculate the relative contribution indicator of a PEC assessment for each land parcel at each receiving environment. Similarly, the scenario delivered load is the delivered component of the scenario source load for each land parcel and is evaluated for each receiving environment connected to that land parcel. The scenario delivered loads are used to calculate the total delivered load for each receiving environment.

3.5. Environmental objectives

A PEC assessment can only be made in the context of defined or assumed objectives for receiving environments. In New Zealand, environmental objectives for freshwater receiving environments are defined by regional land and water plans using procedures set out in the National Policy Statement for Freshwater Management (NPS FM) (Ministry for the Environment, 2017). Under the NPS FM, objectives are numeric and correspond to a quantified 'attribute state' (e.g., lake total nitrogen concentration $< 750 \text{ mg m}^{-3}$). Environmental objectives for coastal receiving environments are defined by the New Zealand Coastal Policy Statement (Department of Conservation, 2010). In both cases, the objectives are based on social, cultural, economic and/or ecological values and are therefore inherently normative.

3.6. Maximum acceptable load

The maximum acceptable load is the maximum contaminant load delivered to a receiving environment that will allow objectives for that receiving environment to be achieved (Steward and Lowe, 2010). A maximum acceptable load is derived for each objective that has been set (or assumed) for a receiving environment. In general, maximum acceptable loads are derived from contaminant load-response relationships, where the variable representing the objective is the response, and the maximum acceptable load is the delivered load that corresponds to the objective. Maximum acceptable loads for a given contaminant will vary between types of receiving environments and types of responses. Maximum acceptable loads will also vary within receiving environments if the objectives vary in stringency. Examples of graduated ranges of stringency for environmental objectives are provided by the National Objectives Framework (NOF) associated with the NPS FM (Ministry for the Environment, 2014) or the establishment of good-moderate status boundaries by EU member states when complying with the Water Framework Directive (Poikane et al., 2014). Both frameworks provide guidance for defining maximum acceptable loads for some contaminants in some receiving environments.

3.7. Pressure

The pressure indicator quantifies the extent to which the capacity

for resource use of the land-water system is utilised in relative terms. Pressure is evaluated as the ratio of the total delivered load in a receiving environment to the maximum acceptable load for that receiving environment. The receiving environment is in shortfall when the total delivered load exceeds the maximum acceptable load (i.e., the ratio is greater than one). Shortfall indicates that, in order to achieve environmental objectives, land parcels connected to the receiving environment are not able to make full use of their productive potential, or must invest in appropriate mitigation strategies to reduce contaminant losses. The receiving environment has headroom when the total delivered load is less than the maximum acceptable load (i.e., the ratio is less than one). When the receiving environment has headroom, capacity for resource use remains; there is room for expansion or intensification of productive activity in the catchment.

Pressure is evaluated for every receiving environment represented on the drainage path. The ratio will vary between receiving environments due to differences in objectives (which determine maximum allowable loads) and differences in total delivered loads. For every land parcel there is a critical point, which is the downstream receiving environment that has the highest pressure. The pressure at the critical point is propagated to all upstream land parcels. The evaluation of critical points is based on analyses of all nodes on a drainage path. It is possible to have multiple critical points in catchments. Hence, the pressure category may vary at sub-catchment to catchment scales. For example, catchments with an estuary that is sensitive to nutrient inputs may impose a critical point that is propagated to all land parcels in the upstream catchment.

3.8. Relative contribution

For each land parcel, the relative contribution indicator of a PEC assessment is evaluated at the critical point corresponding to that parcel. Land parcels upstream of a critical point are effectively competing for a share of the receiving environment's assimilative capacity. The parcels with low relative contributions are more suitable for high contaminant emitting land uses.

The relative contribution of a land parcel is evaluated as follows:

$$\text{Relative contribution}_i = \frac{\text{standardised delivered load}_i - \sum_{j=1}^N (w_j \times \text{standardised delivered load}_j)}{\sum_{j=1}^N (w_j \times \text{standardised delivered load}_j)} \quad (1)$$

where i is the i th land parcel, N is the total number of land parcels upstream of a critical point, w_i is the weighted or proportional area of each land parcel and the standardised delivered load is expressed as a yield (e.g., $\text{kg ha}^{-1} \text{yr}^{-1}$). Hence, relative contribution is negative for land parcels that make contributions that are smaller than the mean and vice versa. The relative contribution of a land parcel depends on the mix of contributing land parcels and therefore varies between receiving environments. The critical point is an appropriate location to consider the relative contribution because it is the most constrained point downstream from a land parcel. The critical point therefore identifies the point at which a land parcel experiences the greatest competition for a share of the assimilative capacity available for resource use.

We note that the relative contribution indicator can also be evaluated using scenario delivered loads. Substituting the scenario delivered load for maximum intensity delivered load in Eq. (1) would provide an indication of those land parcels that, when fully developed, would make the largest contribution.

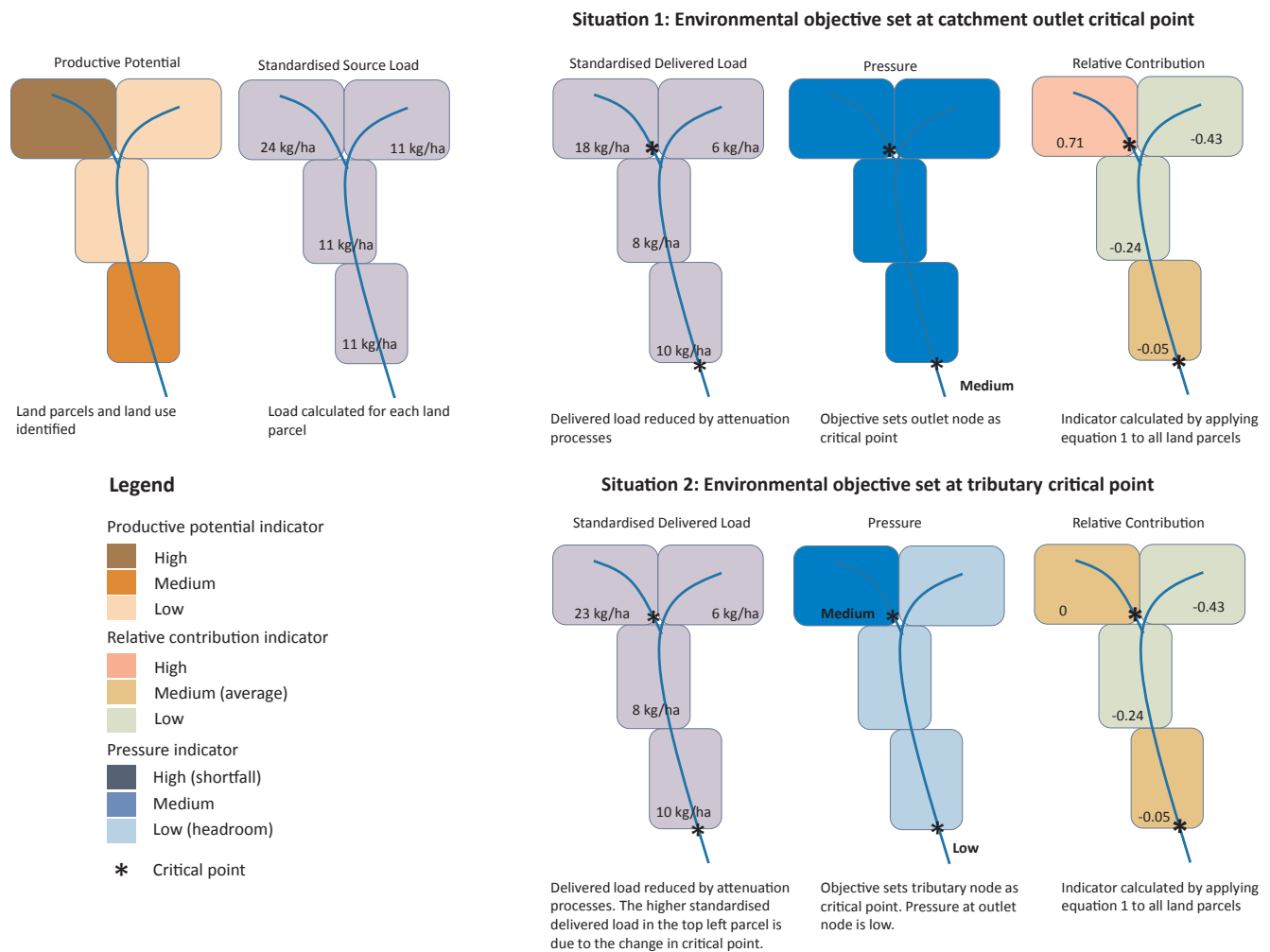


Fig. 2. Schematic diagram showing how indicators for a catchment comprising four land parcels (rectangles), connected to a drainage network (blue lines), can be used to assess sustainable productivity within environmental constraints (PEC) as part of the land use suitability concept. Each panel represents either a map of PEC indicators or the results of steps in the assessment process (e.g. panels entitled Standardised Source Load and Standardised Delivered Load). The two situations show how assessments will differ depending on the configuration of receiving environments as critical points.

3.9. Hypothetical example

A hypothetical example of a PEC assessment for four land parcels is shown in Fig. 2. Two river receiving environment nodes (indicated by asterisks) are shown; one at the bottom of the catchment, the other at the base of the tributary stream. The productive potential differs by land parcel and a map of this indicator is shown in the left of Fig. 2. The standardised source load also differs by land parcel. The standardised delivered loads shown in the centre of Fig. 2 are less than the standardised source loads due to attenuation. Two possible outcomes, depending on the configuration of critical points, are presented in the top and bottom rows of Fig. 2. In the first situation (the top row of Fig. 2), the critical point for all land parcels is the most downstream node. This results in the same (medium) pressure being propagated to all upstream land parcels (i.e., a uniform map of pressure). Accordingly, the standardised delivered load for each land parcel is also calculated using the downstream node. The relative contribution map that results from applying Eq. (1) to the standardised delivered loads is shown on the right side of the top row. In the second situation (bottom row of Fig. 2), the node representing the tributary stream is a critical point, for which the pressure indicator is medium. Pressure at the downstream point is low. These pressure indicator values are propagated to upstream land parcels based on the respective critical points resulting in a variable map of pressure (centre map in the bottom row of Fig. 2). Accordingly, the

standardised delivered load for each land parcel is calculated using its respective critical point. Note the differences in relative contribution maps between the two situations.

3.10. Presenting and mapping the PEC assessment

Levels of each of the three indicators of a PEC assessment (productive potential, relative contribution and pressure) can be expressed as categories. Collectively, these categories provide a description that allows the suitability of a land parcel for a particular land use to be assessed. For example, “High Productive Potential/Low Relative Contribution/Low Pressure” indicates land that is capable of intensive production within the constraints defined by environmental objectives. If the Pressure indicator was “High”, the interpretation would be that environmental constraints are high, but that this parcel is among the more appropriate for high production land uses with the potential for high contaminant losses because its contribution is low compared to others.

Each of the PEC indicators can be shown individually as a static map. Maps of productive potential will produce spatial mosaics with boundaries corresponding to land parcels and variation that reflects differences in the edaphic, topographical and climatic factors that influence the productive potential of land. Maps of relative contribution will also produce mosaics with boundaries corresponding to land

Table 1

Example of how the three PEC indicators could be combined into categories. When applying the land use suitability concept to sustainable productivity within environmental constraints, a single number could provide useful information to stakeholders to judge the suitability of land parcels for certain land uses within a catchment. A simple single ordinal value is shown in each cell ranging from 1 (brown), indicating low “suitability” for intensive land uses with the potential for high contaminant losses to 5 (green) indicating high “suitability”.

	Productive Potential								
	High			Medium			Low		
	Relative Contribution								
	Low	Average	High	Low	Average	High	Low	Average	High
Pressure									
Low (Headroom)	5	5	4	5	4	3	4	3	2
Medium	5	4	3	4	3	2	3	2	1
High (Shortfall)	4	3	1	3	2	1	2	1	1

parcels and variation reflecting differences in the susceptibility of land parcels to contaminant loss, and variation in the degree to which each land parcel's source load is attenuated. Maps of pressure will produce mosaics with boundaries corresponding to the sub-catchments of critical points and variation reflecting differences in the pressure category. Choosing different options for both the land use scenario and the receiving environment objectives will result in changes to maps of relative contribution and pressure. The outputs of the assessment process can also be viewed at any spatial scale using a geographic information system.

The categories for each PEC indicator provide information that inform a variety of land use decisions. These categories can be further summarised to a simpler single categorisation that provides more specific information. For example, Table 1 combines the three indicators into a single ordinal value that judges the suitability of land parcels for high production land uses with the potential for high contaminant losses. The example can be based on the assessed indicators for an individual contaminant (e.g., nitrogen), or by averaging indicators derived for several contaminants, depending on the nature of the farming system under consideration. The ordinal values shown in Table 1 can then be represented spatially in a map that describes the suitability of each land parcel for high production land uses with the potential for high contaminant losses.

4. Data sources and models

A PEC assessment requires a range of spatial data and models to be brought together to collectively represent the components and processes of land-water systems described above. There are multiple options for doing this and the level of detail and accuracy will vary by components and processes, and between geographic locations, depending on data and model availability. We envisage that a PEC assessment as proposed can be implemented nationally, based on available models and data.

At the national scale, the drainage network can be represented by the national digital surface water network, which is widely used in spatial models and environmental classifications (Snelder and Biggs, 2002; Snelder et al., 2005). More detailed representations of the drainage network could include groundwater flow paths and classifications of regional aquifer systems, but these would need to be developed. Lake, wetland and estuary receiving environments can be represented by existing national scale classifications that are integrated with the digital surface water network (Hume et al., 2007; Johnson and Gerbeaux, 2004; Leathwick et al., 2007).

Either LUC or Topoclimate or both systems can be used to assign land parcels to a productive potential category. Advances in assessing land productive potential can be achieved by combining both

approaches and by including information about potential management practices and infrastructure (e.g., irrigation systems) that may increase the inherent productive potential of land (Bartley et al., 2013).

Both standardised and scenario contaminant source loads can be assessed for land parcels using a combination of data describing the edaphic and climatic conditions in combination with models that describe contaminant losses under differing land uses. For example, the OVERSEER model can be employed to represent source loads of nitrogen and phosphorus at the farm scale (Selbie et al., 2013), and the SedNET model can be used to represent sub-catchment and catchment sediment source loads (Dymond et al., 2016). It is also noted that estimates of losses of all four contaminants from different land use groupings are described by the SPARROW and CLUES models for which numerous parameterisations exist at national, regional and catchment scales (Elliott et al., 2005; Elliott et al., 2016). Although SPARROW and CLUES do not explicitly represent spatial variation in contaminant transformation processes (e.g., spatially variable rates of denitrification in shallow groundwater), improved representations of the effects of contaminant transformation on delivered loads are in development (Rivas et al., 2017). Alternatively, existing models that have been developed overseas can be used, such as the Soil Water Assessment Tool (Arnold et al., 1998).

Contaminant load-response relationships used to derive maximum acceptable loads can be obtained from a variety of existing sources or from new research. For example, Robertson et al. (2016) developed large-scale relationships between delivered nitrogen loads and trophic responses in New Zealand estuaries, Latimer and Rego (2010) developed relationships between nitrogen loads and seagrass cover for New England estuaries, and Larned et al. (2015) developed national-scale relationships between dissolved inorganic nitrogen and phosphorus concentrations and in-stream periphyton biomass and cover in New Zealand.

The level of detail and accuracy of data and models have limitations that will be reflected in any PEC assessment. Noteworthy limitations of the models we outline above include incomplete representation of hydrological systems (e.g., surface water-groundwater models), some processes such as attenuation and time lags, and poor ability to predict load/concentration-response relationships. Given the potential for attenuation to strongly affect the suitability of a land parcel, PEC assessments could be significantly improved by incorporating recent research describing spatial variation in attenuation rates (Close et al., 2016) into assessments. There is significant concern in New Zealand regarding the loss of nutrients from land, which has led to the regulation of trophic state objectives for all rivers and lakes (Ministry for the Environment, 2014). It is important therefore that PEC assessments represent constraints on nutrient losses from land that arise from the need to achieve trophic state objectives in receiving environments.

Although relevant nutrient load/concentration-trophic response relationships exist, these are uncertain (Larned et al., 2015). Improvements in PEC assessments will be dependent in part on improving the accuracy of load/concentration-response relationships.

5. Usage, limitations and future development of PEC assessments

PEC assessments are intended to assist with strategic and objective assessments of land for multiple stakeholders. Primary sector industry groups, and regional and central government can use PEC assessments to identify areas where future agricultural development should be encouraged, or where more stringent controls are required, based on environmental objectives in connected receiving environments. The implementation of PEC at the national scale would provide a systematic basis for identifying opportunities and constraints that may support harmonising regulations across regions and encouraging location-appropriate land use choices. For example, PEC assessments could be used in strategic planning to help New Zealand regional councils set freshwater objectives (and water quality and quantity limits to meet them), as stipulated by the NPS FM. In exploring the implications of objectives, PEC assessments can be used by banks to assess environmental risks associated with their clients' current or proposed farming operations. Land investors can use PEC assessments as a strategic screening tool to understand the implications of different locations for the productivity and long-term viability of different land uses.

While PEC assessments have multiple potential uses in land use decision making and land and water planning, there are several limitations. Chief amongst these is the need to tightly define the scope and limitations of a PEC assessment. While we have defined the challenge as “sustained productivity within environmental constraints”, we recognise that within the LUS concept there may be other applications based on different indicators that could either be developed separately or incorporated into PEC assessments to help stakeholders make informed decisions. For example, water availability (e.g., for irrigation), infrastructure, shipping distances and socio-economic conditions (e.g., labour availability) also influence the suitability of different land uses in different locations.

A second limitation is the dependence of PEC assessments on critical points. In reality, the effects of contaminants are manifested at multiple points in a catchment, and the effects often vary continuously with contaminant loading. Contaminant losses in the upstream portions of catchments affect more receiving environments and may therefore have a greater overall impact on environmental values than contaminants that are lost lower in the catchment. Future work could develop methods for integrating the effect of contaminants across multiple receiving environments. Similarly, methods to combine the indicators derived for all four contaminants could be developed and tested.

We recognise that there is potential for future developments that can increase the scope and utility of PEC assessments. In particular, PEC could include consideration of land and water mitigation strategies that reduce source and delivered loads and interventions that increase the resilience in receiving environments to the effects of contaminants (Burns et al., 2014; McDowell and Nash, 2012; Özkundakci et al., 2010). Here, management actions that reduce source loads or increase attenuation are termed mitigations. Mitigation may be carried out on land parcels (e.g., riparian retirement, conservation tillage) or at the interface between land parcels and the drainage network linking land parcels to receiving environments (e.g., denitrifying bioreactors, treatment wetlands). In contrast, strategies that are carried out in the drainage network or in receiving environments are termed interventions. Interventions can operate in three ways: 1) reducing contaminant loads after delivery to the receiving environment (e.g., estuary flushing, alum additions and sediment capping in lakes); 2) increasing resistance to degradation (e.g., shading streams to prevent algal blooms); and 3) enhancing recovery from degradation (e.g., flushing flows to remove river algae and fine sediment from rivers). A list of potential mitigations

and interventions can be found in McDowell et al. (2013).

The most cost-effective mitigations and interventions vary with land use, catchment conditions and receiving environment. Conceptually, mitigations can be represented in PEC assessments by modifying source or delivered loads. Interventions can be represented by modifying delivered loads and maximum acceptable loads (possibly by altering contaminant load-response relationships). Both strategies could alter the relative contribution and/or the pressure indicators.

6. Summary

LUS broadens the early conceptualisations of land suitability to include the wider impacts on the land and environment, and the PEC assessment has been developed as a specific application of LUS. The three indicators in a PEC assessment are intended to facilitate strategic assessments of land production systems in terms of both productivity and environmental constraints. The assessment process allows for presentation in numeric, tabular and spatial formats, and there is substantial flexibility with the framework to allow for assessments to be tailored to various needs of different situations. PEC was developed in the context of existing national land and water policy in New Zealand, which includes the requirement to set objectives for water bodies and associated water quantity and quality limits (Ministry for the Environment, 2017). However, its conceptual basis is applicable to other jurisdictions where productivity goals need to be achieved within constraints defined by environmental objectives.

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